Research in Transportation Economics xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Research in Transportation Economics

journal homepage: www.elsevier.com/locate/retrec

Research paper

Economic appraisal of implementing electric vehicle taxis in Seoul

Seong-Cheol Kang[a,*], Hoyoung Lee[b]

[a] Global Green Growth Institute, 19F Jeongdong Building, 21-15 Jeongdong-gil, Jung-gu, Seoul, 04518, Republic of Korea
[b] Department of Civil and Environmental Engineering, Seoul National University, Gwanak-ro, Gwanak-gu, Seoul, 08826, Republic of Korea

ARTICLE INFO

JEL classification:
D61
H43
L91
Q51
Q54
R40

Keywords:
Electric vehicle taxi
Air pollutant
Greenhouse gas
Economic appraisal
Sustainable transport

ABSTRACT

Global commitments for climate change mitigation and sustainable development have given the electric vehicle renewed attention as a critical building block of sustainable transport. However, the diffusion of electric vehicles has been limited so far. In an effort to facilitate scaled-up deployment of electric vehicles, this paper examines the economic feasibility of replacing the current fleet of fossil fuel taxis in Seoul with electric vehicle (EV) taxis by gradually phasing out the former based on their operational lifetime. In the cost-benefit analysis for such a transition, costs of purchasing vehicles and constructing and maintaining charging infrastructure are estimated based on the market prices and characteristics of taxi transport in Seoul. On the benefit side, the avoided environmental costs due to reduced air pollutants and greenhouse gas emissions are calculated. Traffic assignment is incorporated in the calculation process for a better estimation of the avoided costs through more accurate link flows and speeds on the road network. Savings in fuel and maintenance costs are also estimated. The resultant benefit-cost ratio signifies economic viability of the deployment of EV taxis. The results of the study are encouraging and could strengthen the argument for pushing the transition to electric vehicles forward.

1. Introduction

Transport is fundamental to economic and social development. It generates employment opportunities and drives economic growth within and beyond its own sector. In Europe, for example, the transport sector directly employs around 10 million people and accounts for about 5% of gross domestic product (European Commission, 2017). It has an even larger impact on the economy via other sectors that depend on transport services to move people, goods, and services in an efficient manner. Transport also contributes to social inclusion and community cohesion as well-connected transport systems facilitate interactions in society.

The development of transport systems, however, has also brought negative externalities to society, such as traffic congestion, accidents, and noise. In particular, transport is one of the main sources of greenhouse gas (GHG) emissions and ambient air pollution in urban areas. According to the Intergovernmental Panel on Climate Change (IPCC), globally 14% of GHG emissions in 2010 were released from the transport sector (IPCC, 2014). On the county level, more GHG emissions is attributed to the transport sector if the country is more car-centric and developed in general. For instance, the transport sector of the United States produced 27% of the total GHG emissions in 2015 (EPA, 2017), almost twice the global average in percentage terms. Transport is also responsible for around half of energy-related nitrogen oxide (NO_x) emissions and is an important source of primary particulate matter, $PM_{2.5}$ which affects human health more than any other pollutant. Given the global trend of rapid urbanization with increasing demand for mobility particularly in developing countries, these environmental and health externalities from the transport sector will continue to be exacerbated under the business-as-usual scenario.

Dating back to its invention in the 1800s, the electric vehicle had long been considered as an alternative to the internal combustion engine vehicle but without much success. The Paris Agreement in 2015 setting out the target of limiting the increase in the global average temperature to well below 2 °C above preindustrial levels and pursuing efforts to limit the temperature increase to 1.5 °C (UNFCCC, 2015), however, has given the electric vehicle renewed attention as a critical building block in achieving the transport sector's GHG emissions reduction goals for the Paris Agreement.

Electric vehicles normally do not produce any tailpipe GHG or air pollutant emissions. If well-to-wheel energy used in them is produced through renewable sources, benefits of using electric vehicles are even greater. Despite the intrinsic benefits of electric vehicles, their mass diffusion has proven to be difficult so far. More expensive prices of electric vehicles relative to their fossil fuel counterparts have been a major barrier to their scaled-up deployment. However, the cost of

* Corresponding author.
E-mail addresses: jsc.kang@gggi.org (S.-C. Kang), hoyounglee@snu.ac.kr (H. Lee).

https://doi.org/10.1016/j.retrec.2018.11.007
Received 30 September 2017; Received in revised form 5 October 2018; Accepted 30 November 2018
0739-8859/ © 2019 Elsevier Ltd. All rights reserved.

Please cite this article as: Seong-Cheol Kang and Hoyoung Lee, Research in Transportation Economics, https://doi.org/10.1016/j.retrec.2018.11.007

ARTICLE IN PRESS

batteries, which currently makes up between one-third and half of the vehicle cost, is coming down rapidly and it is projected that the cost of lithium-ion batteries would reach USD 100/kWh by 2023, at which point an entry-level equivalent of a Tesla Model S, for instance, can be purchased for USD 15,000 (Seba, 2014). Inadequate charging stations and long charging time are other impediments to rapid adoption of electric vehicles. As technology advances, driving ranges of electric vehicles will become longer with less charging time, which will relieve the pressure to build many charging stations.

Even with electric vehicles becoming more competitive technically and financially, the public may not opt for these new options quickly except some early adopters partly due to the inertia of using the vehicles familiar to them. This is potentially where the government can intervene and take the initiative to make the transition to electric vehicles for its mobility needs by, for example, replacing its official-purpose vehicles with electric ones. Another fleet of vehicles that might be electrified with relative ease through appropriate policy mandates or incentives from the government is taxis or rental cars.

Taxis in urban areas have the characteristic that their daily travel distances are much longer than those of private cars which usually sit in parking spaces most of the day. Moreover, the idling time of taxis tends to be much longer than that of other vehicles, which leads to higher emissions of GHG and air pollutants. This means that the impact of a fossil fuel taxi on the environment would be disproportionately higher compared to a comparable private vehicle. As such, replacing conventional taxis with electric ones would greatly reduce per vehicle GHG and air pollutants emissions. It will also help raise awareness of electric vehicles as taxis are easily noticed on the streets. Countries like the U.S., Germany, and the Netherlands are actively running electric vehicle (EV) taxies, while London, UK plans to issue new taxi licenses only for electric vehicles from 2018 (Hall, Moultak, & Lutsey, 2017). Under the Seoul Transport Vision 2030, the city government of Seoul, Republic of Korea has made 11 “promises” to provide the citizens with mobility services that are people-oriented, shared, and environmentally friendly (Seoul Metropolitan Government, 2017). Although not explicitly considered in the vision document, EV taxis can be an option to implement one of the promises, “Transforming the transport modes and facilities into environmentally friendly ones.” Currently only a small number of EV taxis (around 60) are in operation in Seoul as a pilot project since 2015.

With a view to full deployment of EV taxis in Seoul, this paper examines the economic feasibility of introducing EV taxis in the form of a policy requirement. We take the approach of replacing the current fleet of taxis with EV taxis by gradually phasing out the former based on their operational lifetime because such a scheme would be implemented most naturally and face least resistance from the taxi owners, if any. To this end, a cost-benefit analysis is conducted where the transport planning model is incorporated to estimate vehicle speeds on the roads more accurately. This is a novel feature that distinguishes this paper from other similar work where the city-wise average vehicle speed is often used, bearing the risk of calculating emission factors inaccurately. The literature on the economic appraisal of introducing EV taxis appears to be scant. Carpenter, Curtis, and Keshav (2014), Tseng and Chau (2017), and Kim, Lee, and Kim (2017) considered the issue but their analysis centered around the profitability of taxi operators, not on the benefits and costs to society.

This paper is organized as follows. In Section 2, characteristics of taxi transport in Seoul are described to set the stage. The calculations of costs and benefits of introducing EV taxis are given in detail in Section 3. How the transport planning model is used within the cost-benefit analysis is explained in the section. In Section 4, findings and conclusions are provided.

2. Taxi transport in Seoul

There are 72,007 taxis in Seoul as of 2016, 49,269 of which are owned by individuals and the remainder by companies. The number of taxis has remained virtually the same since 2012 although the total number of vehicles has steadily increased (see Table 1). This is due to the city government's temporary moratorium on the issuance of new taxi permits in order to maintain an appropriate balance between the supply and demand of taxi services.

Table 1
Registered vehicles and taxis in Seoul (unit: vehicles, %).

Year	Registered Vehicles	Taxis			
		Private	Company	Total	%
2012	2,969,184	49,424	22,801	72,225	2.4
2013	2,973,877	49,398	22,787	72,185	2.4
2014	3,013,541	49,373	22,787	72,160	2.4
2015	3,056,588	49,336	22,760	72,096	2.4
2016	3,083,007	49,269	22,738	72,007	2.3

Table 2
Mode share in Seoul (unit: 1,000 trips/day, %).

Year	Total Trips	Mode Share				
		Passenger Car	Taxi	Bus	Subway/Train	Others
2011	31,885	23.5	7.0	28.0	37.1	4.4
2012	32,150	23.1	6.9	27.4	38.2	4.4
2013	32,516	22.9	6.8	27.1	38.8	4.4
2014	32,690	22.8	6.8	27.0	39.0	4.4
2015	32,410	23.0	6.8	26.5	39.3	4.4

The share of trips made by taxi has remained stable at 6.8–7.0% during the period of 2011–2015 (see Table 2). Considering that the fleet of taxis constitutes only 2.4% of the total registered vehicles for the period, the mode share of taxis is disproportionately large.

The average daily distance driven by a taxi in Seoul is 226.0 km, while that of a private passenger vehicle is only 30.7 km in 2016 (Ahn & Jung, 2016; Korean Statistical Information Service, 2017). Breaking this down further, company taxis travel 274.7 km per day on average as compared to 193.5 km for private taxis. This is because company taxis usually operate in two shifts per day. In theory, company taxis can operate for 365 days per year without any time off. In contrast, private taxis must take the fourth day off after working three days in a row. Due to heavy usage, a company taxi is required by law to be decommissioned and replaced by a new one after 6 years in use. A private taxi can operate a little longer for 9 years. Using the national vehicle registration data, the number of taxis that need to be replaced in 2018 onwards is shown in Table 3. Thus, the current fleet of taxis can be gradually phased out by 2026.

Taxis in Seoul use liquefied petroleum gas (LPG) as fuel. This is considered as a favor to taxi operators as LPG prices are cheaper than those of gasoline or diesel partly due to the fact that a less fuel tax is

Table 3
Replacement demand for taxis based on vehicle age (unit: years, vehicles).

Taxi Vehicle Age		Registered Taxis		Replacement Demand	Year of Replacement
Private	Company	Private	Company		
9	6	1,053	816	1,869	2018
8	5	1,420	1,871	3,291	2019
7	4	3,406	3,785	7,191	2020
6	3	5,180	5,238	10,418	2021
5	2	5,824	5,110	10,934	2022
4	1	5,488	5,918	11,406	2023
3	–	7,028	–	7,028	2024
2	–	8,180	–	8,180	2025
1	–	11,690	–	11,690	2026
Total		49,269	22,378	72,007	

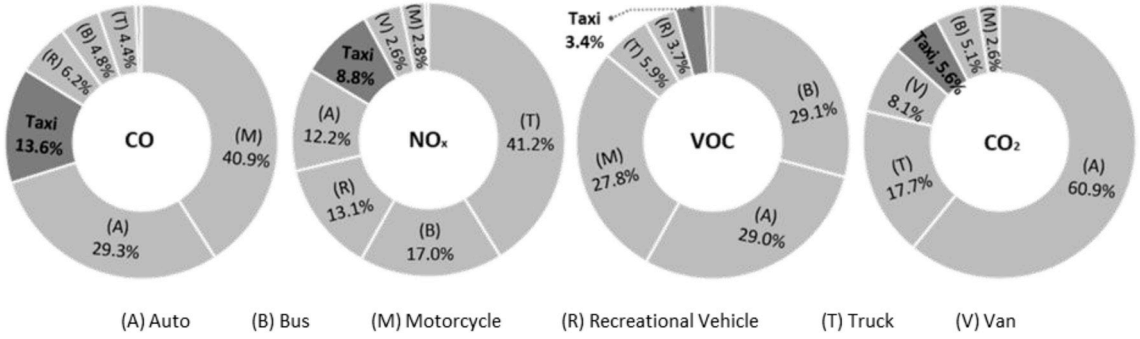

Fig. 1. Air pollutants and CO_2 emissions in road transport in Seoul.[1].

Table 4
Annual emission amount of air pollutants and CO_2 per vehicle (unit: vehicles, kg/vehicle).

	Registered Vehicles	CO	NO_x	VOC	CO_2
Taxi	72,185	144.9	33.5	5.6	8,852.3
Auto	2,390,330	9.4	1.4	1.4	2,901.2

Table 5
Elements of cost and benefit in economic feasibility analysis.[2].

	Elements		Korea	UK	Japan	Germany
Cost	Construction		○	○	○	○
	Purchasing Vehicles		○			
	Operation and Maintenance		○	○	○	○
Benefit	Operating Costs Reduction		○	○	○	○
	Travel Time Reduction		○	○	○	○
	Traffic Accidents Reduction		○	○	○	○
	Environmental Improvements	Air Pollution	○	○	○	○
		GHG	○	○	○	○
		Noise	○	○	○	○
	Parking Availability		○			
	Transport Provider Profitability			○	○	
	Amenities Enhancement				○	
	Physical Activity Promotion			○		
	Improved Reliability			○		
	Option Values			○		
	Regional Development			○	○	○

levied on LPG. According to National Air Pollutants Emission Service (2017), 13.6% of carbon monoxide (CO), 8.8% of NO_x, and 3.4% of volatile organic compound (VOC) in road transport were emitted by taxis in Seoul in 2013. The statistics from National GHG Emission Total Information System (2017) show that 5.6% of CO_2 were attributable to taxis (see Fig. 1). These are substantial proportions considering the less than 3% of vehicle share of taxis

Table 4 shows the annual emission amount of the above air pollutants and GHG per vehicle for taxis and private passenger vehicles in 2013. This backs up our assertion that the impact of a fossil fuel taxi on the environment would be disproportionately higher compared to a comparable private vehicle.

3. Costs and benefits of EV taxis

Economic feasibility studies in Korea are governed by the guidelines from Korea Development Institute (2008). The elements of cost and benefit that can be taken into consideration in the analysis are shown in Table 5. Compared to other countries, it can be said that Korea takes a conservative approach in the analysis as less benefit elements are being considered.

In regard to the cost-benefit analysis of introducing EV taxis, the relevant cost and benefit elements are given in Table 6. The appraisal period is chosen to be 9 years taking into account the operational lifetime of the current fleet of taxis. The discount rate is set to 5.5% as per the guidelines of Korea Development Institute (2008).

Table 6
Cost and benefit elements and parameters considered.

Category	Elements	
Cost	Purchasing Vehicles	
	Charging Infrastructure Construction	
Benefit	Operating Costs Reduction	
	Environmental Improvements	Air Pollution
		GHG
Appraisal Period	9 years	
Discount Rate	5.5%	

3.1. Cost analysis

3.1.1. Purchasing vehicles

The current market prices of the typical LPG taxi (Hyundai Sonata) and the EV taxi being piloted in Seoul (Renault Samsung SM3 Z.E.) are USD 17,201 and 37,776, respectively. We assume that the price of an EV taxi declines as much as the cost of its battery falls. Based on the cost projection of lithium-ion battery for EVs in Seba (2014) (see also Table 16) and the battery size of the EV taxi model being considered (22 kWh), the price of an EV taxi is projected as in Table 7. The price of an LPG taxi, on the other hand, is assumed to be invariant during the appraisal period.[3]

It is assumed that LPG taxis are replaced by EV taxis when their operational lifetime is reached, i.e., 6 years for a company taxi and 9 years for a private taxi. We believe that this replacement scheme would be implemented most naturally and face least resistance from the taxi owners. Based on the replacement demand of taxis identified in Table 3, the additional cost incurred due to the transition to EV taxis is calculated for each year in Table 8.

[1] Recreational vehicles include sports utility vehicles and car-derived vans.

[2] Prepared by the authors based on information from Korean Development Institute; Department for Transport of United Kingdom; Ministry of Land, Infrastructure, Transportation and Tourism of Japan; and German Federal Ministry of Transport.

[3] The vehicle price can be affected by various factors including market competition and inflation. Since there is no anticipated technological advancement that can drive the price of LPG vehicles down substantially, we assume a fixed vehicle price for simplicity. Our survey even shows price increases during the last several years.

ARTICLE IN PRESS

Table 7
EV taxi price (unit: dollars).

Year	2018	2019	2020	2021	2022	2023	2024	2025	2026
Price	37,776	36,742	35,862	35,136	34,520	33,992	33,552	33,178	32,870

Table 8
Purchasing vehicles (unit: vehicles, million dollars).

Year	Taxi Replacement Demand	Vehicle Purchasing Cost		(B) – (A)
		LPG (A)	EV (B)	
2018	1,869	32.1	70.6	38.5
2019	3,291	56.6	120.9	64.3
2020	7,191	123.7	257.9	134.2
2021	10,418	179.2	366.0	186.8
2022	10,934	188.1	377.4	189.4
2023	11,406	196.2	387.7	191.5
2024	7,028	120.9	235.8	114.9
2025	8,180	140.7	271.4	130.7
2026	11,690	201.1	384.3	183.2
Total	72,007			

3.1.2. Charging infrastructure construction

The driving range of the EV taxi model under consideration (Renault Samsung SM3 Z.E.) is 135 km. Since fast charging replenishes 80% of the battery capacity, we assume that EV taxis can travel 108 km before being recharged. Assuming the current average daily distance driven by LPG taxis remains the same (274.7 km for a company taxi, 193.5 km for a private taxi), this would mean that a company EV taxi needs to charge 2.54 times a day whereas a private EV taxi 1.79 times. Using these frequencies, the total daily charging demand is estimated first. In doing so, it should be noted that only three quarters of private EV taxis are on the roads any given day because they are required to take the fourth day off after working three days in a row. Therefore, the total daily charging demand is the three quarters of private EV taxis multiplied by 1.79 plus the number of company EV taxis multiplied by 2.54.

The moments for EV taxis to be recharged will not be uniformly distributed across the day as customer demand for taxis fluctuates over time. By analyzing the digital tachograph data of LPG taxis, Ko, Kim, Nam, and Lee (2017) found that a late hour of Friday is the busiest time for taxis and projected that 11.04% of the daily charging demand will occur in that period. Using this statistic, the maximum hourly charging demand is calculated as the total daily charging demand multiplied by 11.04%. The underlying rationale is that charging infrastructure should be provided enough to accommodate this maximum hourly charging demand.

It takes 30 minutes to fast charge an EV taxi. One of the required specifications of fast charging stations in Korea is that it should be able to charge three vehicles at the same time (with three charging cables). Taking these into account, the number of charging stations to cover the maximum hourly charging demand is obtained by dividing the latter by 6. The current market price of constructing such a fast charging station is USD 39,904 with annual maintenance costs of USD 1,596 (Lee & Kim, 2016). Table 9 summarizes the above calculations along with costs of providing charging stations. The fact that existing charging stations continue to serve some portion of the maximum hourly charging demand in the future, incurring only maintenance costs, is reflected in the calculations.

3.2. Benefit analysis

3.2.1. Environmental improvements

When LPG taxis are replaced by EV taxis, air pollutants and GHG emissions from the former are avoided. Therefore, the first step toward the calculation of the associated benefit is to estimate the amount of avoided emissions. To this end, we employ the emission factors, i.e., the emission amount per km travelled, for CO, NO_x, VOC, and CO_2 for an LPG taxi shown in Table 10 (Ministry of Land, Infrastructure and Transport, 2014; National Institute of Environmental Research, 2013), where Y is the emission amount (g/km) and v is the vehicle speed (km/h).

Table 9
Charging infrastructure construction (unit: vehicles, number of times, million dollars).

Year	EV Taxis in Operation		Total Daily Charging Demand	Maximum Hourly Charging Demand	Additional Charging Stations Needed	Cost
	Private	Company				
2018	1,053	816	3,486	385	64	2.7
2019	2,473	2,687	10,145	1,121	123	5.2
2020	5,879	6,472	24,331	2,688	261	11.1
2021	11,059	11,710	44,590	4,925	373	16.2
2022	16,883	16,820	65,388	7,223	383	17.2
2023	22,371	22,738	87,788	9,697	412	19.0
2024	29,399	22,738	97,223	10,739	174	9.8
2025	37,579	22,738	108,204	11,953	202	11.3
2026	49,269	22,738	123,898	13,687	289	15.2

Table 10
Emission factors for an LPG taxi.[4].

Category		Year of Vehicle Manufacture	Formula
Air Pollutants	CO	Prior to 1999	$Y = 350.12 \times v^{-1.2852}$
		2000–2002	$Y = 53.445 \times v^{-0.8327}$
		2003–2005	$Y = 13.380 \times v^{-0.5948}$
		After 2006	$Y = 46.661 \times v^{-0.9760}$
	NO_x	Prior to 1999	$Y = 3.9363 \times v^{-0.5648}$
		2000–2002	$Y = 4.8692 \times v^{-0.7475}$
		2003–2005	$Y = 2.2994 \times v^{-0.6773}$
		After 2006	$Y = 3.1607 \times v^{-0.5998}$
	VOC	Prior to 1999	$Y = 45.157 \times v^{-1.2485}$
		2000–2002	$Y = 13.598 \times v^{-1.1951}$
		2003–2005	$Y = 6.3304 \times v^{-1.2443}$
		After 2006	$Y = 3.1096 \times v^{-1.1486}$
GHG	CO_2	All	If $v <$ 65.4 km/h, $Y = 1521.36 \times v^{-0.6128}$ If $v \geq$ 65.4 km/h, $Y = 0.0264v^2 - 4.1928v + 279.93$

To obtain vehicle speeds and travel distances of LPG taxis that are necessary for calculating the emission amounts through the emission factors, we perform the traffic assignment step of the four-stage transport planning model (Ortuzar & Willumsen, 2011) using the Seoul metropolitan road network and the associated origin-destination traffic flow data provided by Korea Transport Database (2017). Figure 2 shows the road network and it is divided into 1,273 traffic analysis zones.

The assignment of the origin-destination traffic flows on the network is conducted according to Wardrop's first principle, also known as user equilibrium, “The journey times on all the routes actually used are equal, and less than those which would be experienced by a single vehicle on any unused route” (Wardrop, 1952). This equilibrium is mathematically equivalent to a Nash equilibrium. In doing traffic assignment, it is of paramount importance to calibrate parameters of link performance functions so that the flows assigned on the links of the road network are sufficiently close to the observed ones on those links. Once the calibration process is done, data of interest such as link flows, link speeds, and travel distances can be obtained from the results of

[4] For LPG taxis, the emission factors for other air pollutants including $PM_{2.5}$ are not available.

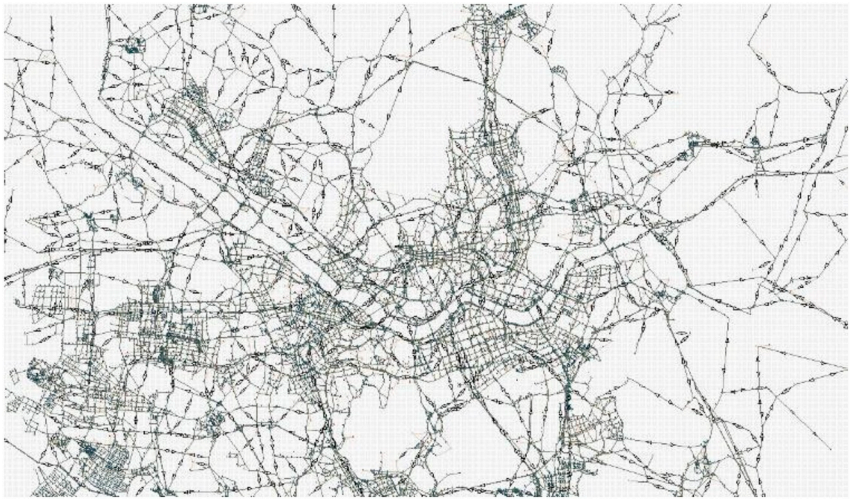

Fig. 2. Road network of Seoul Metropolitan area.

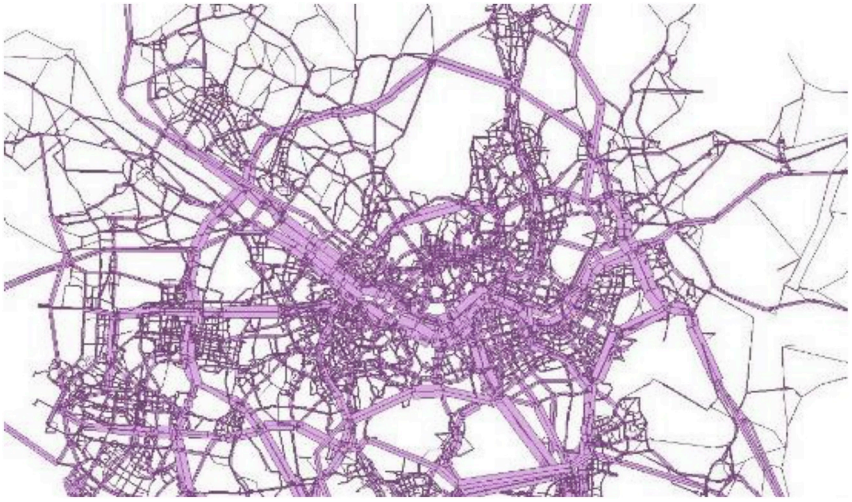

Fig. 3. Result of traffic assignment.

traffic assignment. Fig. 3 is the graphical representation of the traffic assignment results obtained from the transport planning software Emme 3 (the thicker the link, the higher the traffic volume on it). The algorithm for deterministic user equilibrium traffic assignment in Emme 3 is based on the Frank-Wolfe algorithm (Frank & Wolfe, 1956). The stopping criteria for the assignment are the maximum 200 iterations or 0.1% for the relative gap on link travel times.

The emission amounts for each year calculated by combining the emission factors with the results of traffic assignment, i.e., link flows, link speeds, and travel distances, are shown in Table 11, where 2017 is the base year, representing the business-as-usual scenario. To aid the interpretation of the table, 48,216 private LPG taxis and 21,922 company LPG taxis combinedly produce 15,986 tonnes of CO, 2,960 tonnes of NO_x, 900 tonnes of VOC, and 1,348,257 tonnes of CO_2 in 2018. Thus, 463 tonnes of CO, 86 tonnes of NO_x, 26 tonnes of VOC, and 39,038 tonnes of CO_2 are avoided compared to the base year because 1,053 private LPG taxis and 816 company LPG taxis are replaced by EV taxis. Similar interpretation applies to other years.

The final step of calculating the benefit is to monetize the avoided emissions. To do so, we need the “social costs” of air pollutants and GHG emissions. The guidelines of Korea Development Institute (2008) are to use USD 8.81, 10.60, 10.24, and 0.05 as the social costs of a kilogram of CO, NO_x, VOC, and CO_2, respectively. Multiplying avoided emission amounts from Table 11 by the social costs, Table 12 shows the avoided emission costs as LPG taxis are gradually replaced by EV taxis.

Table 11
Emission amounts from LPG taxis (unit: vehicles, tonnes/year).

Year	LPG Taxis in Operation		CO	NO_x	VOC	CO_2
	Private	Company				
2017	49,269	22,738	16,449	3,046	926	1,387,295
2018	48,216	21,922	15,986	2,960	900	1,348,257
2019	46,796	20,051	15,102	2,796	851	1,273,690
2020	43,390	16,266	13,218	2,448	744	1,114,829
2021	38,210	11,028	10,528	1,949	593	887,971
2022	32,386	5,918	7,767	1,438	437	655,077
2023	26,898	–	4,793	887	270	404,247
2024	19,870	–	3,541	656	199	298,624
2025	11,690	–	2,083	386	117	175,688
2026	–	–	–	–	–	–

One may argue that EV taxis still produce GHG emissions not from their tailpipes but from the generation of the electricity they use, unless it is generated from renewable sources. In this case, the avoided costs of CO_2 in Table 12 could be overestimates. To address this issue, we consider how electricity is produced currently and in the future in Korea. Table 13 shows the mix of power generation in Korea in 2017 and the target for 2030 (Ministry of Trade, Industry and Energy, 2017). As can be seen, the most notable change is a significant uptake of renewables-based electricity from 6.2% in 2017 to 20.0% by 2030.

ARTICLE IN PRESS

Table 12
Avoided emission costs (unit: vehicles, million dollars).

Year	Replaced LPG Taxis		Avoided Cost				
	Private	Company	CO	NO_x	VOC	CO_2	Total
2018	1,053	816	4.1	0.3	0.9	1.9	7.1
2019	1,420	1,871	11.9	0.8	2.6	5.4	20.7
2020	3,406	3,785	28.5	1.9	6.3	12.9	49.6
2021	5,180	5,238	52.2	3.4	11.6	23.7	90.9
2022	5,824	5,110	76.5	5.0	17.0	34.7	133.3
2023	5,488	5,918	102.7	6.7	22.9	46.6	178.9
2024	7,028	–	113.7	7.4	25.3	51.6	198.2
2025	8,180	–	126.6	8.3	28.2	57.5	220.5
2026	11,690	–	144.9	17.8	32.3	65.8	260.8

Table 13
Mix of power generation in Korea.

Year	Nuclear	Coal	LNG	Renewables	Oil	Pumped Storage	Total
2017	30.3%	45.4%	16.9%	6.2%	0.6%	0.7%	100%
2030	23.9%	36.1%	18.8%	20.0%	0.3%	0.8%	100%

According to Ministry of Trade, Industry and Energy (2014), coal, LNG, and oil produce 0.823 kg, 0.3625 kg, and 0.7018 kg of CO_2 respectively when generating 1 kWh of electricity. Therefore, the power generation mix in 2017 results in the emission of 0.4391 kg of CO_2 per kWh of electricity generated. This amount is expected to decrease to 0.3674 kg of CO_2 in 2030 due to the increased use of renewables. The amount of upstream CO_2 emissions associated with the operation of EV taxis for each year can then be estimated by multiplying the CO_2 emissions per kWh by the number of EV taxis and the annual average travel distance, and then dividing the result by the fuel efficiency. Since the power generation mix is not available between 2018 and 2029, the CO_2 emissions per kWh for those years are interpolated. Table 14 shows new estimates for the avoided costs of CO_2 and the total avoided costs when the upstream CO_2 emissions from electricity generation are taken into consideration.

The process taken above to estimate the benefit from avoided air pollutants and GHG emissions is depicted in Fig. 4.

3.2.2. Operating costs reduction

To estimate the reduction in operating costs, we compare fuel and maintenance costs between LPG and EV taxis. Table 15 shows the prevailing data on fuel efficiency and fuel price for LPG and EV taxis collected from vehicle manufacturers' websites, Korea National Oil Corporation, and Korean Electric Power Corporation.

The maintenance cost of an LPG taxi is estimated at USD 2,831 per year (Seoul Metropolitan Government, 2013). Since EV vehicles have a simpler structure with considerably fewer parts than internal combustion engine vehicles, it is expected that EV taxis would be much cheaper to maintain compared to LPG taxis. Maintenance costs for EV taxis, however, are not available, so we borrow the assertion in Seba (2014) that an EV vehicle would require 90% less money on repairs during the lifetime of the car. In addition to this mundane maintenance cost, the cost of battery replacement is also taken into account. The recommended battery replacement cycle of the EV taxi model under consideration is 200,000 km. Considering the annual driving distances of private and company taxis, it is assumed that the battery is replaced every 4 years for a private EV taxi and 3 years for a company EV taxi. To reflect dropping battery costs in the analysis, we use the EV lithium-ion battery cost projection made by Seba (2014) shown in Table 16.

Based on the data and assumptions made above, Table 17 calculates, in the case of private taxis, operating costs of LPG and EV taxis. The resultant cost savings from transitioning to EV taxis are also given. The same calculations for company taxis are shown in Table 18.

Table 14
Avoided emission costs in consideration of CO_2 emissions from EV taxis (unit: vehicles, million dollars).

Year	Replaced LPG Taxis		Avoided Cost				
	Private	Company	CO	NO_x	VOC	CO_2	Total
2018	1,053	816	4.1	0.3	0.9	1.3	6.5
2019	1,420	1,871	11.9	0.8	2.6	3.7	19.0
2020	3,406	3,785	28.5	1.9	6.3	8.9	45.6
2021	5,180	5,238	52.2	3.4	11.6	16.5	83.7
2022	5,824	5,110	76.5	5.0	17.0	24.3	122.8
2023	5,488	5,918	102.7	6.7	22.9	32.6	164.9
2024	7,028	–	113.7	7.4	25.3	36.3	182.9
2025	8,180	–	126.6	8.3	28.2	40.7	203.7
2026	11,690	–	144.9	17.8	32.3	46.8	241.8

3.3. Economic feasibility

To assess the economic feasibility of replacing LPG taxis with EV taxis, the costs and benefits determined in the previous subsection are combined in Table 19 and their net present values are calculated. For the environmental benefits from avoided emissions, figures in Table 14 are used.[5] From the benefit-cost ratio shown below, it is concluded that the gradual deployment of EV taxis in Seoul would be economically feasible.

Among the anticipated improvements with regard to electric vehicles are increased battery capacity and faster charging time due to technological advances. Table 20 shows how the benefit-cost ratio changes as these improvements occur, all other factors remaining unchanged.

4. Conclusions

To keep pace with the Paris Climate Agreement and the UN Sustainable Development Goals, it becomes more important than ever to transform transport systems into greener and more sustainable ones. These global commitments have given the electric vehicle renewed attention as a critical building block of sustainable transport. Countries like UK and France will ban sales of fossil fuel vehicles from 2040, which is expected to propel sales of alternative fuel cars including electric vehicles. Nevertheless, the diffusion of electric vehicles has been disappointing so far and various factors are getting in the way of their mass deployment on the roads, some of which may not be fully controllable by the government.

In a small attempt to breathe new life into this gridlock, this study investigated the economic feasibility of replacing the current fleet of LPG taxis in Seoul with EV taxis. Taxis along with rental cars could be a fleet of vehicles that might be electrified with relative ease through appropriate policy mandates or incentives from the government. We took the approach of replacing the current LPG taxis with EV taxis by gradually phasing out the former based on their operational lifetime because such a scheme would be implemented most naturally and face least resistance from the taxi owners, if any.

In the cost-benefit analysis for such a transition to EV taxis, costs of purchasing vehicles and constructing and maintaining charging infrastructure were estimated based on the market prices and characteristics of taxi transport in Seoul. On the benefit side, the avoided environmental costs due to reduced air pollutants and GHG emissions were calculated. The traffic assignment step of the four-stage transport planning model was incorporated in the calculation process for a better

[5] If upstream CO_2 emissions from electricity generation are not considered and therefore the benefits from avoided CO_2 emissions in Table 12 are used, the benefit-cost ratio increases to 2.26.

ARTICLE IN PRESS

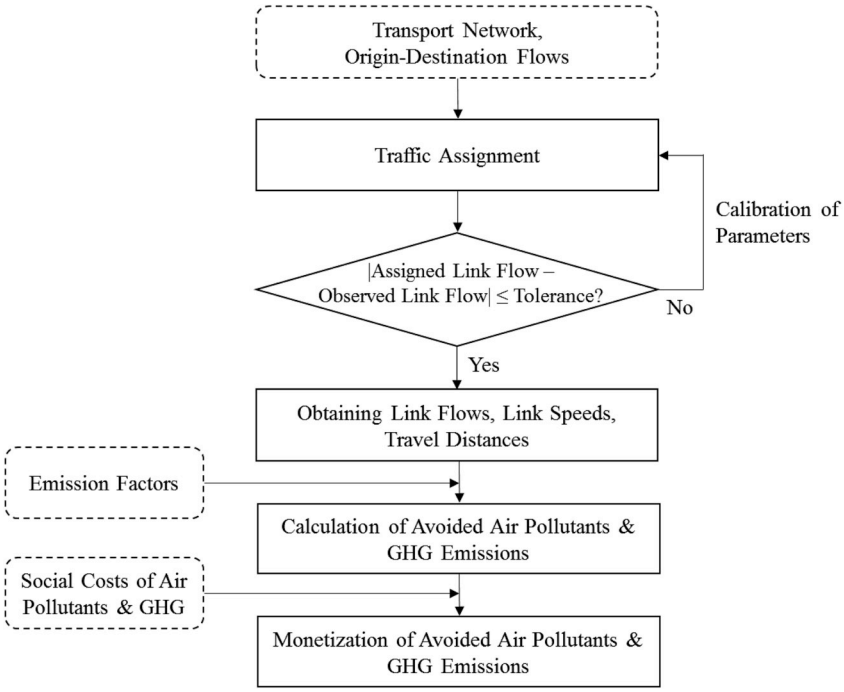

Fig. 4. Process of estimating environmental benefit based on traffic assignment.

Table 15
Fuel efficiency and fuel price.

	Fuel Efficiency	Fuel Price
LPG Taxi	7.9 km/L	USD 0.75/liter
EV Taxi	4.8 km/kWh	USD 0.15/kWh

Table 16
EV lithium-ion battery cost projection.

Year	2017	2018	2019	2020	2021	2022	2023	2024	2025
Cost (USD/kWh)	296	249	209	176	148	124	104	87	73

estimation of the avoided costs through more accurate link flows and speeds on the road network. Savings in fuel and maintenance costs were also estimated. The resultant benefit-cost ratio was 2.20, signifying economic viability of the deployment of EV taxis.

Under the guidelines for economic appraisal in Korea, we conducted a fairly detailed assessment of costs and benefits. We should point out that our analysis focused on economic feasibility in the societal context and did not carefully examine implications of the proposed transition toward EV taxis on policy and management dimensions, except the underpinning proposition that phasing-out of LPG taxis based on operational lifetime could be implemented in the form of a policy mandate. What factors influence users to adopt EVs is an important research question but out of the scope of this paper in the assumed context of a mandated EV transition in the taxi industry. We however acknowledge the importance of ex-ante assessment of the preferences of potential EV users in fostering the diffusion of EVs beyond in the taxi industry and note, as relevant analyses, the work of Marcucci, Le Pira, Carrocci, Gatta, and Pieralice (2017) and Serafini, Nigro, Gatta, and Marcucci (2018) where the potential adoption of an innovative mobility option, called crowdshipping, in urban areas was assessed via a survey and stated preference exercises. We also recognize limitations of cost-benefit analysis as well laid out in Jones, Moura, and Domingos (2014), including non-consensus on what kinds of benefits and costs can be

Table 17
Reduction in operating costs for private taxis (unit: vehicles, million dollars).

Year	Replacement Demand	Costs of LPG Taxis (A)		Costs of EV Taxis (B)			(A) – (B)
		Fuel	Maintenance	Fuel	Maintenance	Battery Replacement	
2018	1,053	5.3	3.0	1.7	0.3	–	6.2
2019	1,420	12.4	7.0	4.1	0.7	–	14.6
2020	3,406	29.6	16.6	9.7	1.7	–	34.8
2021	5,180	55.6	31.3	18.3	3.1	3.4	62.1
2022	5,824	84.9	47.8	27.9	4.8	3.9	96.1
2023	5,488	112.5	63.3	37.0	6.3	7.8	124.7
2024	7,028	147.8	83.2	48.7	8.3	11.9	162.2
2025	8,180	189.0	106.4	62.2	10.6	11.6	210.9
2026	11,690	247.8	139.5	81.6	13.9	14.3	277.5

ARTICLE IN PRESS

Table 18
Reduction in operating costs for company taxis (unit: vehicles, million dollars).

Year	Replacement Demand	Costs of LPG Taxis (A)		Costs of EV Taxis (B)			(A) – (B)
		Fuel	Maintenance	Fuel	Maintenance	Battery Replacement	
2018	816	7.8	2.3	2.6	0.2	–	7.3
2019	1,871	25.6	7.6	8.4	0.8	–	24.0
2020	3,785	61.6	18.3	20.3	1.8	3.2	54.7
2021	5,238	111.5	33.2	36.7	3.3	6.1	98.5
2022	5,110	160.1	47.6	52.7	4.8	12.6	137.7
2023	5,918	216.4	64.4	71.2	6.4	16.3	186.9
2024	–	216.4	64.4	71.2	6.4	18.6	184.5
2025	–	216.4	64.4	71.2	6.4	11.4	191.7
2026	–	216.4	64.4	71.2	6.4	15.6	187.5

Table 19
Economic feasibility (unit: million dollars).

Year	Yearly Value		Net Present Value	
	Cost	Benefit	Cost	Benefit
2018	41.1	20.0	41.1	20.0
2019	69.5	57.6	65.9	54.6
2020	145.3	135.1	130.6	121.4
2021	203.0	244.2	172.9	208.0
2022	206.6	356.6	166.7	287.9
2023	210.6	476.5	161.1	364.6
2024	124.7	529.6	90.4	384.1
2025	141.9	606.3	97.6	416.8
2026	198.3	706.8	129.2	460.6
Total			1,055.6	2,317.9
B/C			2.20	

Table 20
Sensitivity analysis.

Charging Time	Battery Capacity (Driving Range)		
	135 km	200 km	300 km
30 min	2.20	2.26	2.29
15 min	2.27	2.31	2.32

incorporated in the analysis as evident in Table 5. Nevertheless, the results of this study are encouraging and could strengthen the argument for pushing the transition to electric vehicles forward.

References

Ahn, K., & Jung, S. (2016). *Effectiveness of taxi app operational Patterns and Management of taxi call industry. Seoul, Republic of Korea.* The Seoul Institute.

Carpenter, T., Curtis, A. R., & Keshav, S. (2014). The return on investment for taxi companies transitioning to electric vehicles. *Transportation, 41*(4), 785–818.

EPA (2017). *Sources of greenhouse gas emissions.* https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions/ 17.09.22.

European Commission (2017). *Transport sector economic analysis.* https://ec.europa.eu/jrc/en/research-topic/transport-sector-economic-analysis/ 17.09.22.

Frank, M., & Wolfe, P. (1956). An algorithm for quadratic programming. *Naval Research Logistics Quarterly, 3*, 95–110.

Hall, D., Moultak, M., & Lutsey, N. (2017). *Electric vehicle capitals of the world.* Washington DC, United States: The International Council on Clean Transportation.

IPCC (2014). Summary for policymakers. In O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, & K. Seyboth, (Eds.). *Climate change 2014: Mitigation of climate change. Contribution of working group III to the fifth assessment report of the inter-governmental Panel on climate change.* Cambridge, United Kingdom: Cambridge University Press.

Jones, H., Moura, F., & Domingos, T. (2014). Transport infrastructure project evaluation using cost-benefit analysis. *Procedia - Social and Behavioral Sciences, 111*, 400–409.

Kim, J., Lee, S., & Kim, K. S. (2017). A study on the activation plan of electric taxi in Seoul. *Journal of Cleaner Production, 146*, 83–93.

Ko, J., Kim, D., Nam, D., & Lee, T. (2017). Determining locations of charging stations for electric taxis using taxi operation data. *Transportation Planning and Technology, 40*(4), 420–433.

Korean Development Institute (2008). *Studies on guidelines of feasibility study for road and rail transport project* (5th ed.). (Seoul, Republic of Korea).

Korean Statistical Information Service (2017). *Driving distance by vehicle usage, type, and registered city & county.* http://kosis.kr/statHtml/statHtml.do?orgId=426&tblId=DT_426001_N004/ 17.08.28.

Korean Transport Database (2017). *Seoul metropolitan area passenger O/D traffic update in 2014.* https://www.ktdb.go.kr/www/index.do/ 17.09.27.

Lee, S., & Kim, J. (2016). *A study on the network-based electric vehicle charging infrastructure construction.* Ulsan, Republic of Korea: Korea Energy Economics Institute.

Marcucci, E., Le Pira, M., Carrocci, C. S., Gatta, V., & Pieralice, E. (2017). Connected shared mobility for passengers and freight: Investigating the potential of crowd-shipping in urban areas. *2017 5th IEEE international Conference on Models and Technologies for intelligent transportation systems (MT-ITS)* (pp. 839–843). .

Ministry of Land Infrastructure and Transport (2014). *Vehicle greenhouse gas emission coefficient (Tier 3).* 17.09.27 http://www.molit.go.kr/USR/I0204/m_45/dtl.jsp?gubun=&search=&search_dept_id=&search_dept_nm=&old_search_dept_nm=&psize=10&search_regdate_s=&search_regdate_e=&srch_usr_nm=&srch_usr_num=&srch_usr_year=&srch_usr_titl=&srch_usr_ctnt=&lcmspage=1&idx=12602/.

Ministry of Trade Industry and Energy (2014). *The 2nd national energy master plan.* (Seoul, Republic of Korea).

Ministry of Trade Industry and Energy (2017). *The 8th basic plan for long-term electricity supply and demand.* (Seoul, Republic of Korea).

National Air Pollutants Emission Service. (2017). http://airemiss.nier.go.kr/Accessed 17.08.30.

National GHG Emission Total Information System. (2017). http://netis.kemco.or.kr/ Accessed 17.08.30.

National Institute of Environmental Research (2013). *National air pollutant emission estimation method handbook (III). Incheon, Republic of Korea.*

Ortuzar, J. D., & Willumsen, L. G. (2011). *Modelling transport* (4th ed.). United Kingdom: John Wiley & Sons.

Seba, T. (2014). *Clean disruption of energy and transportation.* California, United States: Clean Planet Ventures.

Seoul Metropolitan Government (2013). *A study on taxi transportation cost analysis and improvement of pricing system.* (Seoul, Republic of Korea).

Seoul Metropolitan Government (2017). *Seoul traffic vision 2030.* http://english.seoul.go.kr/policy-information/traffic/seoul-traffic-vision-2030/ 17.09.28.

Serafini, S., Nigro, M., Gatta, V., & Marcucci, E. (2018). Sustainable crowdshipping using public transport: A case study evaluation in rome. *Transportation Research Procedia, 30*, 101–110.

Tseng, C. M., & Chau, C. K. (2017). Viability analysis of electric taxis using New York city dataset. *Proceedings of the Eighth International Conference on Future Energy Systems,* 328–333.

UNFCCC (2015). *Adoption of the Paris agreement.* (Paris).

Wardrop, J. G. (1952). Some theoretical aspects of road traffic research. *ICE Proceedings of the Institution of Civil Engineers, 1*(3), 325–362.